forests

MDPI

Article

The Environmental Impact of Poplar Stand Management: A Life Cycle Assessment Study of Different Scenarios

Simone Cantamessa, Laura Rosso *, Achille Giorcelli and Pier Mario Chiarabaglio

CREA—Research Centre for Forestry and Wood, Strada Frassineto 35, 15033 Casale Monferrato, AL, Italy; simone.cantamessa@crea.gov.it (S.C.); achille.giorcelli@crea.gov.it (A.G.); piermario.chiarabaglio@crea.gov.it (P.M.C.)

* Correspondence: laura.rosso@crea.gov.it

Abstract: The circular economy will play an important role in the reduction of carbon emissions and poplar might be one of the winning choices according to sustainable development. As for agricultural crops, high-quality production is strictly related to genetic variability and best management practice. The main objective of this study was to analyze different stand management options to quantify differences on carbon emission and environmental impacts. Moreover, the study was focused on the assessment of differences between standard poplar management for veneer and poplar management according to sustainable production (such as the PEFC certification scheme). The system boundaries embraced fertilization (inorganic or organic), agricultural operations, machinery, and field emissions associated with poplar cultivation. The environmental impacts were quantified by a life cycle assessment (LCA) calculation using SIMAPRO software v8.0 with different databases. The primary data of poplar stands were collected during a decades-long Italian experience. A reduction of carbon emissions was observed in the stand managed with MSA clones (Case "Mezzi PEFC"), and negative emissions were observed due to organic fertilization (scenarios 7m-29 t CO_2-eq ha^{-1} and 26M-129 t CO_2-eq ha^{-1}). In all cultivation scenarios, the environmental impacts were lower than conventional crops in the study area, such as corn. A higher impact was observed in the 26M scenario with oversized machinery for stand management. These data can also contribute to poplar stand modeling and represent a basis for future research developments in this field.

Keywords: life cycle assessment; poplar stand management; environmental impact

check for updates

Citation: Cantamessa, S.; Rosso, L.; Giorcelli, A.; Chiarabaglio, P.M. The Environmental Impact of Poplar Stand Management: A Life Cycle Assessment Study of Different Scenarios. *Forests* **2022**, *13*, 464. https://doi.org/10.3390/f13030464

Received: 19 January 2022
Accepted: 12 March 2022
Published: 16 March 2022
Corrected: 5 September 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In Italy, since the early 1900s, the landscape of plains and hills has been characterized by specialized plantations to cultivate poplar destined for the plywood sector [1]. Due to their economic importance, poplars benefit from the same innovations common to other crops, giving rise to competition for the use of fertile soils [2]. Hence, the fundamental aspects are adopting the best agronomic practices and genetic selection to improve production and obtain wood with low environmental and economic costs. Traditional Italian poplar cultivation applies agronomic criteria to produce valuable wood for the processing industry, i.e., plywood. The management of these plantations involves techniques with reduced environmental impacts, low emissions, and reasonable maintenance of biodiversity compared to the main crops [3]. Due to their fast growth, poplar stands can provide microhabitats in a short time compared to broadleaves [4], influencing the presence of birds and insects [5]. Poplar plantations can also increase the biodiversity of epiphytic lichens and mosses [6] The most commonly used cultivation system in Italy is based on one or two-year-old poplar unrooted stems for establishing plantations of hybrid clones; in particular, the most common clone is the hybrid *Populus xcanadensis* 'I-214' with a planting density of 250–300 trees per hectare and a rotation of 10 years. Poplar is susceptible to several factors affecting growth and yield. A critical factor for poplar growth is water availability: poplar

is considered the most sensitive tree to water deficit [7]. The natural poplar populations are located near water bodies or with the water table depth at 100–150 cm [8]. Due to high evapotranspiration rates, poplar stand water demand is relevant [9]. According to Allen and collaborators [10], the evapotranspiration of water is directly related to the crop coefficient (Kc); compared to the main crops, poplar has the highest Kc [11].

Poplar is susceptible to infection by some fungi and insects, and climate change could directly or indirectly influence phytopathogens' propagation or activities [12]. Breeding programs created clones that are resistant to the leaf diseases and woolly aphid (clones with greater environmental sustainability—the acronym for Italian 'Maggior Sostenibilità Ambientale', named MSA clones) to reduce chemicals and pesticides [13].

High-yield productions depend on fertilization [14–16]. Inorganic fertilizers are expensive and not environmentally friendly, so organic fertilizers are encouraged as an alternative since they could improve soil fertility and carbon stock in the soil [17].

A life cycle assessment (LCA) analysis is a holistic methodology with the goal to analyze the pathway of products, processes, and services to assess the environmental impacts. Moreover, LCA analysis is a decision-support tool that may help to identify more sustainable solutions [18,19]. Most scientific literature is focused on the short rotation coppice (2–4 years) for bioenergy production [20–22], and little is known about the environmental impact of poplar stands for veneer purposes (ten years of rotation). This study aimed to evaluate the environmental impacts of different poplar stand managements and draw up a database with the inputs that will be available for future research. According to LCI ISO 14041:1999, a life cycle inventory analysis was performed for each stand management phase, with all the raw material, energy, and emissions related to agricultural inputs. Different options from our databases were simulated with SIMAPRO software to test their sustainability performances. The overall environmental impacts were identified, and four scenarios were considered through an LCA study "from cradle-to-gate".

2. Materials and Methods

2.1. Goal and Scope

This study evaluated the environmental impact of different poplar stand managements with a cradle-to-gate perspective using four different poplar tree plantation systems located in the Po Valley, North-West Italy. An in-depth understanding of poplar management could promote sustainability, compensate for the emissions of other crops, and enhance sustainable agricultural policies.

2.2. System Description and Boundaries

The poplar plantation was the same for each scenario: a square layout of 6 × 6 m with a density of 278 trees ha^{-1} and a growth rotation of 10 years for industrial purposes (e.g., veneer). As reported by Chiarabaglio et al. [19], the cultivation model is described in Figure 1. The transportation of the organic and inorganic inputs was taken into account by assuming a mean distance of 30 km. Three main phases were considered for stand managements: (a) soil preparation and plantation, (b) cultivation for ten years, and (c) harvesting. The system boundaries did not include post-harvesting activities (e.g., wood furniture production).

Four scenarios were considered with different managements of watering, plant protection fertilization, and machinery, as reported below:

- "Mezzi Standard" poplar management is a poplar plantation with inorganic fertilization, weeds and diseases are chemically and mechanically controlled, when necessary, with tailored machinery, and the 'I-214' poplar clone alone. In this experiment, the field was watered by sprinkling;
- "Mezzi PEFC" poplar management is a poplar plantation with the same treatments for the first scenario, with 'I-214' poplar clone and 10% MSA clones [23]. In this experiment, the field was watered by sprinkling;

- The "7m" scenario is a poplar plantation fertilized with compost (a one-time application of 7 tons ha^{-1}), plant protection with eco-friendly treatments, tailored machinery, and the 'I-214' poplar clone alone. In this experiment, no irrigation was applied due to the availability of the water table;
- The "26M" scenario is a poplar plantation fertilized with compost (applied two times for a total of 26 tons ha^{-1}), plant protection with eco-friendly treatments, oversized machinery, and the 'I-214' poplar clone alone. In this experiment, no irrigation was applied due to the availability of the water table.

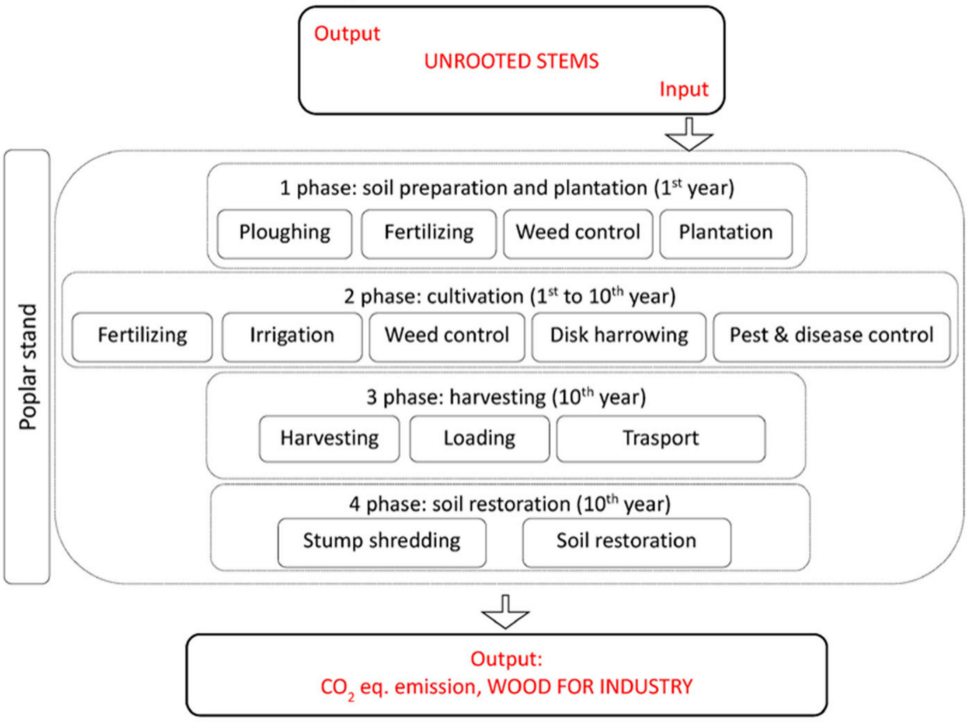


Figure 1. System boundary.

2.3. Functional Unit

The choice of a functional unit is an important step that allows the quantification of all inputs and outputs and the comparison between other LCA results [24]. Different functional units (FUs) can be selected with LCA's application to agricultural processes. From the point of view of agricultural production systems, the best choice for the functional unit is the area [25,26], so we decide to define it as 1 hectare of poplar stand.

2.4. Data Collection

Data were collected from 2000 to 2021 in several experimental fields of CREA, located in North-West Italy (Figure 2). The field condition was the same for each scenario: the average annual temperature was around 13 °C; the annual total rain was between 700 and 800 mm, with about 400 mm during the vegetative season, from March to October. The soil texture was classified as sandy loam. Poplar was in rotation with common herbaceous crops, most frequently corn in all the areas considered.

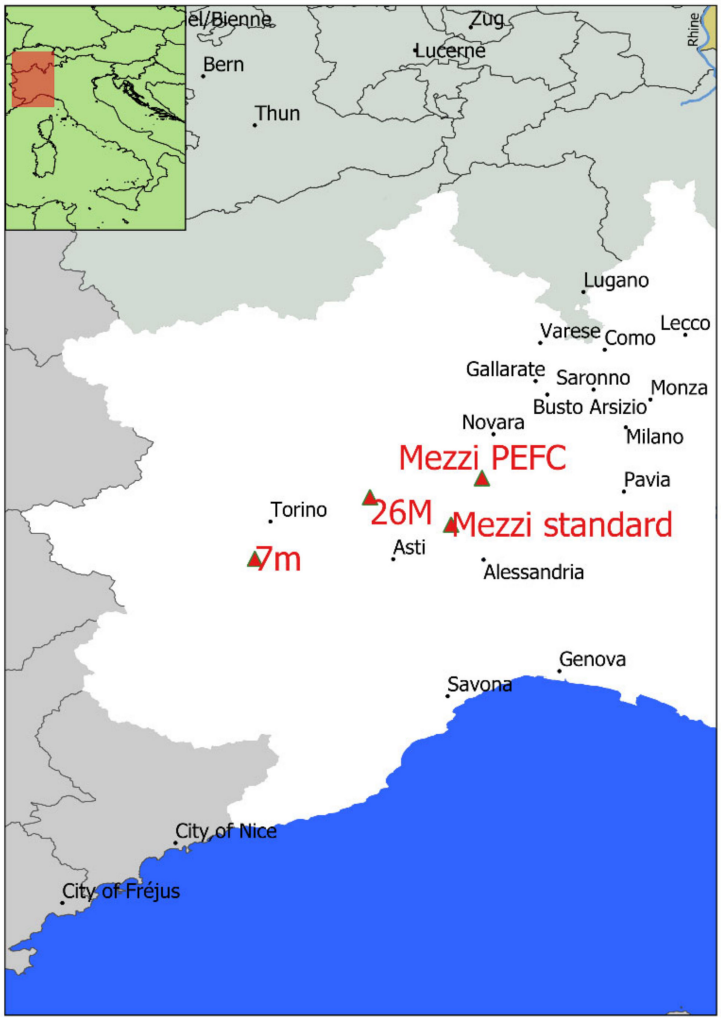


Figure 2. Locations of the field experiments (North-West Italy). Red triangle=locations of field experiment.

The CREA-Research Centre for Forestry and Wood, Casale Monferrato (Italy), drew up a database from field trials carried out for almost 20 years in the farm "Mezzi" (180 hectares). Table S1 provides all the inputs collected about soil management, poplar plantation, and harvesting; work times, machine type, engine power for different operations, and agrochemical inputs are reported. The work times were recorded at each agricultural operation during poplar stand management. The same operations were used in the 7m and 26M scenarios with different fertilization, weed management, watering, and plant protection treatments.

The fuel consumption was calculated according to Guerrieri et al. [27], relating it to unit area (F; kg ha^{-1}):

$$F = Sc \times P \times d \times t$$

where Sc = specific fuel consumption (fixed to 0.25 kg kWh^{-1}), P = maximum engine power in kW, d = power utilization factor in % (maximum demand of power related to agricultural operation), and t = time in hours.

2.5. Life Cycle Impact Assessment (LCIA)

The LCA analysis was conducted according to two ISO norms, 14,040 and 14,044 [28,29]. The study is based on primary data reported by Chiarabaglio et al. [19] that was analyzed with the SIMAPRO 8.0 databases (Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI). The impacts on climate change of the four models were calculated, comparing the CO_2-eq total emissions and utilizing the IPCC 2013 GWP 100a method [30]. Concerning compost

as a substitute for inorganic fertilization, we considered the compost as avoided life cycle waste [31]. The emissions of each cultural operation were firstly calculated separately, then they were added to obtain the total emissions. LCA computations were carried out by applying the ReCiPe methods for evaluating the water consumption, greenhouse gas emissions, impacts on human health, effects on ecosystem biodiversity, and impacts on primary resources [32]. Both mid- and endpoint levels were used to acquire an overview of the environmental impacts (midpoint level) and damages (endpoint level) of the four models considered.

3. Results and Discussion

Several surveys agree that the critical points for sustainability are, above all, the production of plant protection products and fertilizers as well as their use in the field and the use of fuels associated with them for application [33–36]. All the comparisons have considered the cultivation operations carried out in the examined poplar plantations concerning the four analyzed models, except for irrigation, which was present only in the traditional and PEFC models of the Mezzi farm. The "Mezzi" standard model differs from the PEFC models due to the presence of 10% poplar clones with greater environmental sustainability, which are resistant or tolerant to the main poplar biotic adversities [37]. Moreover, the PEFC model provides tillage of the soil up to the third year and, from the fourth, the shredding of weeds and localized treatments for Saperda (*Saperda carcharias* L.), with a lower impact due to the avoidance of glyphosate. The adoption of the PEFC model leads to a reduced environmental impact. Moreover, the 7m and 26M scenarios differ from the standard and PEFC managements due to the use of different fertilization of the soil, using compost instead of chemical fertilizers.

Table 1 reports the ReCiPe midpoint impact categories. As shown, the PEFC standard reduced the impacts from a range between 1% and 8%. At the same time, the 7m and 26M scenarios had a positive trend, which is ascribed to the lower use of several inorganic fertilizers and plant protection chemicals, according to Romero-Gamez et al. [38]. Concerning the impact categories terrestrial acidification, terrestrial ecotoxicity, and human toxicity, in the 26M scenario there was an increase due to oversized machinery and compost production. Analyzing the water consumption during a rotation of 10 years, the PEFC model showed a 6% reduction due to lower processing and phytosanitary treatments, which were possible thanks to MSA poplar clones' resistance to the main adversities compared to the "Mezzi" standard. Regarding water-use efficiency, cases 7m and 26M are interesting; using organic fertilizer (compost of urban solid waste mixed with pruning residues of urban green waste) with a water content of 30% helped recover water. In the 7m scenario, 3.5 m^3 of water equivalent was saved thanks to 7 tons of compost in the first year. In the 26Mscenario, where the contribution of compost was higher and equal to 26 tons (10 tons during the soil preparation phase, 8 in the second, and 8 in the third year), the water-saving was 13 m^3. Both the 7m and 26M cases were more environmentally friendly regarding phytosanitary treatments (pest and diseases); against woolly aphid (*Phloeomyzus passerinii* Sign.) they used mineral oil as an alternative to conventional pesticides, with low impacts on the ecosystem [39]. The 26M scenario had a higher equivalent water consumption than the 7m scenario due to more powerful operating machines, and the oversizing of machinery also increased the use of fossil resources. Concerning the stratospheric ozone depletion and land use, the scores showed that PECF management decreased the impact, while the use of organic soil improver increased the ozone depletion; these results are similar to [40] and are related to compost production.

Table 1. Comparison (in %) between the environmental results per functional unit from the "Mezzi" standard and the remaining cropping systems under assessment.

Impact Categories	Unit	Mezzi Standard	Mezzi PEFC	7m	26M
Terrestrial acidification	kg SO_2-eq	48.3	94	82	124
Terrestrial ecotoxicity	kg 1,4-DCB *	18,503	95	103	127
Freshwater ecotoxicity	kg 1,4-DCB *	165	94	42	89
Marine ecotoxicity	kg 1,4-DCB *	205	97	52	95
Human toxicity	kg 1,4-DCB *	6254	92	93	169
Water consumption	m^3	17,460	99	5	6
Stratospheric ozone depletion	kg CFC11-eq **	0.016	98	364	1298
Land use	m^2a crop-eq.	140.4	97	278	979
Fossil resource scarcity	kg oil-eq.	3431.3	94	81	110

The percentages for each system and impact category indicate the percentage relative to the Mezzi farm system. The irrigation inputs were applied only in the traditional model and PEFC. * DCB indicates 1,4-Dichlorobenzene. ** CFC11 indicates trichlorofluoromethane.

Table 2 reports the results calculated by the IPCC 2013 impact assessment method for the Mezzi cases (standard and PEFC) and the 7m and 26M scenarios are split up for the three phases reported in Figure 1. The difference between the standard model and the PEFC model was equal to 6% due to fewer plant protection products, the avoidance of glyphosate, and lower water consumption. The use of organic fertilizers also contributed to significantly reducing the emission of greenhouse gases; in fact, Table 2 shows how fertilization by compost in the 7m case allowed CO_2 sequestration equal to 29 tons due to the contribution, in the first year, of 7 tons of compost. In the 26M scenario, where the contribution of compost in the cultivation rotation shift was 26 tons, the sequestration was equal to 129 tons of CO_2.

Table 2. IPCC 2013 GWP for a time frame of 100 years expressed as Kg of CO_2 equivalent.

Case	Phase 1	Phase 2	Phase 3	Total
Mezzi Standard	2680	6821	1038	10,539
Mezzi PEFC	2601	6270	1038	9909
7m	2047	−32,025	1102	−28,876
26M	−51,090	−79,180	1346	−128,924

The comparison with crops showed interesting results; the cultivation of corn produces emissions equal to 4.2 tons per hectare in one year [41] against 10.5 tons of the "Mezzi" Standard management, which was the most impactful among the considered scenarios. The rotation shift of poplar is ten years, so poplar cultivation has a three times lower greenhouse gas impact index than corn (if compared both in a shift of ten years).

The analysis of the effects on human health (Figure 3A) according to the ReCiPe endpoint method demonstrated the more sustainable potential of the PEFC model over the conventional one (Mezzi standard, 8% less) due to a lower use of plant protection products and an avoidance of glyphosate. Moreover, the 7m and 26M stand management options led to a positive effect; fertilization by compost avoided waste production and had lower impacts on human health. Comparing these results against crops, the impact of poplar on human health is lower: for example, for the cultivation of tomatoes in greenhouses in Spain [42], the index shows 0.065 years of disability for just one year, while in the case of "Mezzi" standard cultivation, reported the same value, but for ten years of cultivation. Concerning tomato management for ten years, the impact on human health value would be ten times higher than for poplar. Moreover, for corn [43], the values (0.196 per year) are almost thirty times higher than those of poplar.

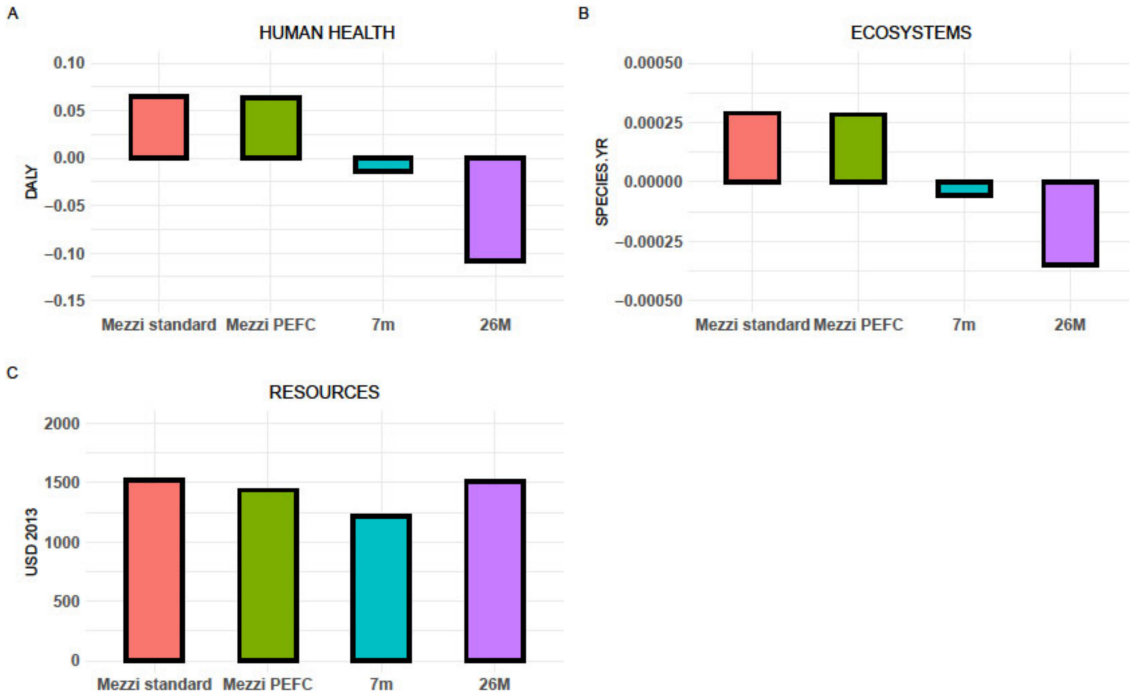


Figure 3. (**A**) Measurement of the effects on human health expressed in years lived, with a worse quality of life in a 10-year rotation. (**B**) Effects on ecosystems expressed in the number of extinct species per year in a 10-year rotation. (**C**) Resource consumption in USD2013 (monetary cost) over a 10-year rotation.

Moreover, regarding the impact on ecosystems (Figure 3B), expressed as the number of extinct species per year, PEFC cultivation reported values 7% lower than the traditional model. The 7m and 26M scenarios led to negative values, thanks to the positive effects of compost fertilization and the avoided waste treatment. Compared with other crops, the values are one hundred times lower than tomato cultivation [32] on a scale of ten years.

Regarding the consumption of resources (Figure 3C), it should be noted that the use of compost produces a more significant impact due to the processing required for the transformation of MSW (municipal solid waste) and wood chips from pruning into organic fertilizer that can be used in the field. If the PEFC model allows a reduction of the impact of 6% compared to the standard one, 26M case reached the same value as the "Mezzi" standard. This result is due to oversized machinery that leads to greater fuel consumption. The 7m scenario, which uses compost and an eco-friendly plant protection treatment, showed a decrease of 22% compared to the standard model. However, the reduction of resource availability in each scenario is lower than tomato production (225 USD2013 ha^{-1} y^{-1}) [44].

The "Mezzi" standard produced 158 m^3 of poplar wood per hectare; the "Mezzi" PEFC produced 197 m^3, with an increase of 24.7% compared to the traditional one with the clone 'I-214'. The 7m and 26M scenarios obtained 240 m^3 from a 10-year rotation of poplar wood with the clone 'I-214'. Considering that the wood density of the clone 'I-214' is 290 kg m^{-3} and that of the MSA clone is 330 kg m^{-3}, the "Mezzi" standard poplar plantation with clone 'I-214' alone sequestered 84 tons of CO_2 in 10 years, while PEFC models with 10% MSA clones sequestered 119 tons of CO_2; the 7m and 26M cases sequestered 128 tons of CO_2.

4. Conclusions

This study shows that the effect on the environment is strictly related to the management of a poplar stand and the choice of inputs, mostly fertilization and plant protection products. Thanks to the LCA analysis carried out with the SIMAPRO software, it was possible to quantify the impacts of poplar cultivation of the Italian standard, PEFC model, and two cases. The analyses showed that the adverse effects of poplar stands on ecosystems

and human health are lower than the considered crops. The obtained results are according to surveys carried out by the CREA Forestry and Wood Center. The use of arable land produces a higher perturbation that leads to a greater reduction in the community of edaphic micro-arthropods than the poplar stands [45], enhancing biodiversity. Moreover, the use of MSA clones, as suggested by PEFC, reduces pesticides and chemicals. Soil fertilization with compost allowed the reduction of CO_2 emissions according to environmental sustainability, avoiding waste production and disposal in landfills [46]. The 7m and 26M scenarios showed that fertilization is an important point for CO_2 reduction; the use of compost reduces the production of carbon dioxide and both the cases led to negative emissions values. The analyses also showed that the oversizing of agricultural machinery led to a higher impact on the environment and human health, with higher management costs.

The results and the agricultural operations in Table S1 represent an important step for future research developments focused on carbon stocks and a higher percentage of MSA clones.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13030464/s1, Table S1: primary data.

Author Contributions: Conceptualization, P.M.C., A.G. and S.C.; methodology, P.M.C., A.G., L.R. and S.C.; software, P.M.C. and S.C.; validation, P.M.C., A.G. and L.R.; formal analysis, P.M.C. and S.C.; investigation, P.M.C. and A.G.; resources, P.M.C.; data curation, P.M.C., A.G., L.R. and S.C.; writing—original draft preparation, P.M.C. and S.C.; writing—review and editing, P.M.C., A.G., L.R. and S.C.; visualization, S.C.; supervision, P.M.C. and A.G.; project administration, P.M.C.; funding acquisition, P.M.C. All authors have read and agreed to the published version of the manuscript.

Funding: A part of the results was carried out from the projects VigoForPoplar (Piemonte Region-PSR 16.1.1 NO. 20201093034) and Carter (Veneto Region PSR 16.2.1 NO. 4115583).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Castro, G.; Fragnelli, G.; Zanuttini, R. *La Pioppicoltura e il Compensato di Pioppo Dell'industria Italiana*; Edizioni Lampi di Stampa: Milano, Italy, 2014.
2. Sedjo, R. The Economic Contribution of Biotechnology and Forest Plantations in Global Wood Supply and Forest Conservation. In *Proceedings First International Symposium on Ecological and Societal Aspects of Transgenic Plantations*; College of Forestry, Oregon State University: Corvallis, OR, USA, 2001; pp. 29–46.
3. Pellegrino, E.; Di Bene, C.; Tozzini, C.; Bonari, E. Impact on soil quality of a 10-year-old short-rotation coppice poplar stand compared with intensive agricultural and uncultivated systems in a Mediterranean area. *Agric. Ecosyst. Environ.* **2011**, *140*, 245–254. [CrossRef]
4. Michel, A.K.; Winter, S. Tree microhabitat structures as indicators of biodiversity in Douglas-fir forests of different stand ages and management histories in the Pacific Northwest, U.S.A. *For. Ecol. Manag.* **2009**, *257*, 1453–1464. [CrossRef]
5. Jastrzębska, E.Z. Poplar for Biodiversity? Comparison of Lichen Communities in Stands of Balsam Poplar, Hybrid Larch, Silver Birch and Norway Spruce; Second Cycle, A2E; SLU. Southern Swedish Forest Research Centre: Alnarp, Sweden, 2020; Available online: https://stud.epsilon.slu.se/16126/ (accessed on 11 March 2022).
6. Randlane, T.; Tullus, T.; Saag, A.; Lutter, R.; Tullus, A.; Helm, A.; Tullus, H.; Pärtel, M. Diversity of lichens and bryophytes in hybrid aspen plantations in Estonia depends on landscape structure. *Can. J. For. Res.* **2017**, *47*, 1202–1214. [CrossRef]
7. Tschaplinski, T.J.; Tuskan, G.A.; Gunderson, C.A. Water-stress tolerance of black and eastern cottonwood clones and four hybrid progeny. I.Growth, water relations, and gas exchange. *Can. J. For. Res.* **1994**, *24*, 364–371. [CrossRef]
8. Sun, S.J.; He, C.; Qiu, L.; Li, C.; Zhang, J.S.; Meng, P. Stable isotope analysis reveals prolonged drought stress in poplar plantation mortality of the Three-North Shelter Forest in Northern China. *Agric. For. Meteorol.* **2018**, *252*, 39–48. [CrossRef]
9. Fischer, M.; Trnka, M.; Kučera, J.; Deckmyn, G.; Orság, M.; Sedlák, P.; Žalud, Z.; Ceulemans, R. Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech-Moravian Highlands. *Agric. For. Meteorol.* **2013**, *181*, 43–60. [CrossRef]

10. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; FAO—Food and Agriculture Organization of the United Nation: Rome, Italy, 1998.
11. Paris, P.; Tosi, L.; Tarchi, M.; Trani, A.; Ascenzi, F. *Pioppo, Grandi Risparmi Con la Sub-Irrigazione*; Terra e Vita: Milano, Italy, 2013; Available online: https://terraevita.edagricole.it/wp-content/uploads/sites/11/2015/01/BA_13_03_Pioppo.pdf (accessed on 11 March 2022).
12. Chen, T.; Nan, Z. Effects of phytopathogens on plant community dynamics: A review. *Acta Ecol. Sin.* **2015**, *35*, 177–183. [CrossRef]
13. Coaloa, D.; Facciotto, G.; Chiarabaglio, P.M.; Giorcelli, A.; Nervo, G. Cloni di pioppo a maggior sostenibilità ambientale (MSA). *Sherwood–For. Ed Alberi Oggi* **2016**, *216*, 31–34.
14. Paris, P.; Di Matteo, G.; Tarchi, M.; Tosi, L.; Spaccino, L.; Lauteri, M. Precision subsurface drip irrigation increases yield while sustaining water-use efficiency in Mediterranean poplar bioenergy plantations. *For. Ecol. Manag.* **2018**, *409*, 749–756. [CrossRef]
15. Dimitriou, I.; Mola-Yudego, B. Nitrogen fertilization of poplar plantations on agricultural land: Effects on diameter increments and leaching. *Scand. J. For. Res.* **2017**, *32*, 700–707. [CrossRef]
16. Krzyżaniak, M.; Stolarski, M.J.; Warmiński, K. Life cycle assessment of poplar production: Environmental impact of different soil enrichment methods. *J. Clean. Prod.* **2019**, *206*, 785–796. [CrossRef]
17. Diacono, M.; Montemurro, F. Long-term effects of organic amendments on soil fertility. In *Sustainable Agriculture*; Springer: Dordrecht, The Netherlands, 2011; Volume 2, pp. 761–786.
18. Horne, R.; Grant, T.; Verguese, K. Life Cycle Assessment—Principles, Practice and Prospects. *Austral Ecol.* **2010**, *35*, 117–118.
19. Chiarabaglio, P.M.; Deidda, A.; Bergante, S.; Castro, G.; Facciotto, G.; Giorcelli, A.; Pagliolico, S.; Carbonaro, C. Life Cycle Assessment (LCA): New poplar clones allow an environmentally sustainable cultivation. *Ann. Silvic. Res.* **2020**, *45*, 72–82.
20. Schweier, J.; Molina-Herrera, S.; Ghirardo, A.; Grote, R.; Díaz-Pinés, E.; Kreuzwieser, J.; Haas, E.; Butterbach-Bahl, K.; Rennenberg, H.; Schnitzler, J.P.; et al. Environmental impacts of bioenergy wood production from poplar short-rotation coppice grown at a marginal agricultural site in Germany. *GCB Bioenergy* **2017**, *9*, 1207–1221. [CrossRef]
21. Schweier, J.; Schnitzler, J.-P.; Becker, G. Selected environmental impacts of the technical production of wood chips from poplar short rotation coppice on marginal land. *Biomass Bioenergy* **2016**, *85*, 235–242. [CrossRef]
22. San Miguel, G.; Corona, B.; Ruíz, D.; Landholmb, D.; Laina, R.; Tolosana, E.; Sixto, H.; Cañellas, I. Environmental, energy and economic analysis of a biomass supply chain based on a poplar short rotation coppice in Spain. *J. Clean Prod.* **2015**, *94*, 93–101. [CrossRef]
23. Corona, P.; Bergante, S.; Castro, G.; Chiarabaglio, P.M.; Coaloa, D.; Facciotto, G.; Gennaro, M.; Giorcelli, A.; Rosso, L.; Vietto, L.; et al. *Linee di Indirizzo per una Pioppicoltura Sostenibile*; Rete Rurale Nazionale, Consiglio per la Ricerca in Agricoltura e L'analisi Dell'Economia Agraria: Roma, Italy, 2018.
24. Panesar, D.K.; Seto, K.E.; Churchill, C.J. Impact of the selection of functional unit on the life cycle assessment of green concrete. *Int. J. Life Cycle Assess.* **2017**, *22*, 1969–1986. [CrossRef]
25. González-García, S.; Bacenetti, J.; Negri, M.; Fiala, M.; Arroja, L. Comparative environmental performance of three different annual energy crops for biogas production in Northern Italy. *J. Clean. Prod.* **2013**, *43*, 71–83. [CrossRef]
26. Bacenetti, J.; Fusi, A.; Negri, M.; Guidetti, R.; Fiala, M. Environmental assessment of two different crop systems in terms of biomethane potential production. *Sci. Total Environ.* **2014**, *466–467*, 1066–1077. [CrossRef]
27. Guerrieri, M.; Fedrizzi, M.; Antonucci, F.; Pallottino, F.; Sperandio, G.; Pagano, M.; Figorilli, S.; Menesatti, P.; Costa, C. An innovative multivariate tool for fuel consumption and costs estimation of agricultural operations. *Span. J. Agric. Res.* **2016**, *14*, 209. [CrossRef]
28. International Organization for Standardization (ISO). *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. 2nd ed. ISO: Geneva, Switzerland, 2006.
29. International Organization for Standardization (ISO). *ISO 14044*; Environmental Management: Life Cycle Assessment. Requirements and Guidelines. Requirements and Guidelines; ISO: Geneva, Switzerland, 2006.
30. Intergovernmental Panel on Climate Change. *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: New York, NY, USA, 2013.
31. Vicentin, R.; Masín, C.E.; Lescano, M.R.; Zalazar, C.S. Poultry litter stabilization by two-stage composting-vermicomposting process: Environmental, energetic and economic performance. *Chemosphere* **2021**, *281*, 130872. [CrossRef] [PubMed]
32. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
33. Pelletier, N.; Arsenault, N.; Tyedmers, P. Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: Life cycle perspectives on Canadian canola, corn, soy, and wheat production. *Environ. Manag.* **2008**, *42*, 989–1001. [CrossRef] [PubMed]
34. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental impact of different agricultural management practices: Conventional vs. Organic agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [CrossRef]
35. Prashar, P.; Shah, S. *Impact of Fertilizers and Pesticides on Soil Microflora in Agriculture*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 331–361.
36. Rahman, K.M.A.; Zhang, D. Effects of fertilizer broadcasting on the excessive use of inorganic fertilizers and environmental sustainability. *Sustainability* **2018**, *10*, 759. [CrossRef]

37. Gennaro, M.; Giorcelli, A. The biotic adversities of poplar in Italy: A reasoned analysis of factors determining the current state and future perspectives. *Ann. Silvic. Res.* **2019**, *43*, 41–51.
38. Romero-Gámez, M.; Audsley, E.; Suárez-Rey, E.M. Life cycle assessment of cultivating lettuce and escarole in Spain. *J. Clean. Prod.* **2014**, *73*, 193–203. [CrossRef]
39. Nile, A.S.; Kwon, Y.D.; Nile, S.H. Horticultural oils: Possible alternatives to chemical pesticides and insecticides. *Environ. Sci. Pollut. Res.* **2019**, *26*, 21127–21139. [CrossRef]
40. Martínez-Blanco, J.; Muñoz, P.; Antón, A.; Rieradevall, J. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. *J. Clean. Prod.* **2011**, *19*, 985–997. [CrossRef]
41. Noya, I.; González-García, S.; Bacenetti, J.; Arroja, L.; Moreira, M.T. Comparative life cycle assessment of three representative feed cereals production in the Po Valley (Italy). *J. Clean. Prod.* **2015**, *99*, 250–265. [CrossRef]
42. Antón, A.; Torrellas, M.; Núñez, M.; Sevigné, E.; Amores, M.J.; Muñoz, P.; Montero, J.I. Improvement of agricultural life cycle assessment studies through spatial differentiation and new impact categories: Case study on greenhouse tomato production. *Environ. Sci. Technol.* **2014**, *48*, 9454–9462. [CrossRef] [PubMed]
43. Liang, L.; Wang, Y.; Ridoutt, B.G.; Lal, R.; Wang, D.; Wu, W.; Wang, L.; Zhao, G. Agricultural subsidies assessment of cropping system from environmental and economic perspectives in North China based on LCA. *Ecol. Indic.* **2019**, *96*, 351–360. [CrossRef]
44. Canaj, K.; Mehmeti, A.; Cantore, V.; Todorović, M. LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study. *Environ. Sci. Pollut. Res.* **2020**, *27*, 6960–6970. [CrossRef] [PubMed]
45. Chiarabaglio, P.M. Aspetti Ambientali e Servizi Ecosistemi Della Pioppicoltura. Available online: http://confagricolturaveneto.it/wp-content/uploads/2017/01/Chiarabaglio-Rovigo.pdf (accessed on 27 December 2021).
46. Decreto Legislativo 3 Aprile 2006, n. 152. Norme in Materia Ambientale. (GU n. 88 del 14.04.2006—Suppl. Ordinario n. 96). Available online: http://www.camera.it/parlam/leggi/deleghe/06152dl.htm (accessed on 26 September 2012).